

POLARIZATION ARTEFACTS CORRECTION PROCEDURE FOR A SPECTRO-POLARIMETRIC GONIOMETER

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ABSTRACT

A new goniometric device for spectro-polarimetric BRDF measurements is under development. This goniometer will measure linear and circular polarization of materials. Different instrument quality tests were realized in order to identify factors affecting the measured spectra and to obtain functional relationship between the instrument output and the real reflective properties of the materials. The most limiting of all factors influencing measured spectra was the polarization sensitivity of the spectrometer. Moreover, optical fiber bundle connected to the spectrometer input has unpredictable behavior in polarized light.

In this paper, we present the artefacts produced by sensitivity of the spectrometer to the polarized light and describe the adequate measurement procedure to maintain instrument response under control and to acquire reliable BRDF measurements.

Index Terms— Polarimetric BRDF, goniometer, ASD spectrometer, polarimetric sensitivity, optic fiber bending

1. INTRODUCTION

A new spectro-polarimetric goniometer is under development at DRDC Valcartier (Fig. 1). This goniometer will measure the surface reflectance with various combinations of source-sensor angle geometries, wavelength and polarization conditions, including linear and circular polarization. It will be used to acquire accurate material reflectance signatures and produce a signature database.



Figure 1. The DRDC goniometer

A considerable effort was done to optimize and calibrate the instrument and to reduce the measurement artefacts in order to produce the Bidirectional Reflectance Distribution Function (BRDF) [1] signatures as reliable as possible.

In this paper we present the results of the instrument characterization which point to very high polarization sensitivity of the ASD spectrometer and optical fiber instability. An adequate measurement procedure to maintain instrument response under control and to acquire reliable BRDF measurements is also presented.

2. INSTRUMENT DESCRIPTION

The principal originality of this goniometer is the design of the optical head which allows to obtain same spectral response everywhere in the field of view (FOV) although fragmented spectral response of the ASD spectrometers' input optics [1]. Second, it uses a pair of motorized filter wheels which allow various combinations of clear aperture, polarizers and quarterwave waveplates. For practical reasons, the selected spectrometer is an ASD field spectro-radiometer (ASD FieldSpec4) [2]. Its optical input is built with an optical fiber bundle that makes it easy to use. Only the optical head has to be mounted on the goniometer, the main body of the spectrometer remains aside. This design option was retained because it allows the reduction of the volume and weight on the mobile sensor component. However, as it will be shown further, this choice was not without consequences. ASD FieldSpec4 has a 350nm to 2500nm waveband. The waveband of the Moxtek polarizers is a good match for this spectrometer. For the circular polarization measurement, two Super-Achromatic True Zero-Order waveplates (APSAW) allowed us to cover the most important part of this waveband: one for 400-800 nm and other one for 800-1600nm band respectively.

3. POLARIZATION SENSITIVITY

Different instrument quality tests were realized in order to identify factors affecting the measured spectra and to obtain functional relationship between the instrument output and the real reflective properties of the target. The most striking and limiting of all factors influencing measured spectra was the polarization sensitivity of the ASD spectrometer and the instability due to optical fiber bending.

3.1. Effect of optical fiber bending in non-polarized light

Taking in account that the spectrometer optical fiber will be the element in constant movement during measurement cycle, we tested the effect of the optical fiber bending on the input signal.

The first tests in non-polarized light show that the transmittance variation for unstressed fiber translations (case 1,

Fig. 2) are approximately 0.2%. This is visible in the zoomed part of Fig. 2. Stressing furthermore the optical fiber (case-2 and 3, Fig.2), the spectrum begin to degrade considerably. Transmittance variations for sever fiber bending (case 3, red line, Fig.2): is up to 10%. Finally, the optical fiber is returned to its original unstressed position (black line), hoping retrieving the original spectrum. But a persistent error of 0.1% remains, which is in the instrument margin of error.

A similar experiment is repeated for 'gentle' stresses. This time, no loop is done in the optical fiber. It is simply laterally displaced (translated), simulating the motion done by the goniometer optical head. In these cases, the transmittance errors are less than 0.2%. Thus, for the goniometer, a signal variation of 0.2% is expected due to the fiber displacement.

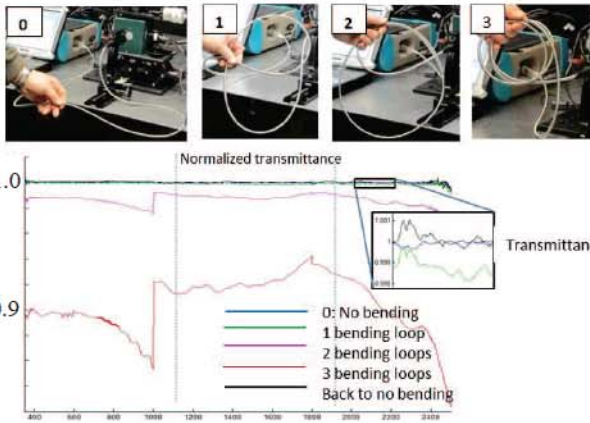


Figure 2. Relative spectra acquired for different optical fiber bending in unpolarized light.

3.2. ASD spectrometer sensitivity to polarized light

The picture drastically changes when the input light is polarized. The ASD spectrometer (as all other spectrometer that uses a grating or beam splitter) is highly sensitive to the polarization of the input light. This is clearly demonstrated in the results presented in Fig. 3, where a polarizer is placed between the emitting integrating sphere and the spectrometer entrance. If the spectrometer was not sensitive to the polarization, the rotation of the polarization would simply attenuate the signal. However, the spectral response of the instrument is completely modified for different orientation of the input polarization.

Several observations can be done from this graph:

- The polarization sensitivity increase with the wavelength. While this sensitivity is relatively low in the visible, it is considerable in SWIR1 and extreme in the SWIR2 band.
- Curiously, some wavelengths (visible and SWIR1 at 1200nm) seem not affected by the polarization.
- Near 1330nm the spectrometer response has like inflection point for all polarization orientations.

3.3. Effect of optical fiber bending in polarized light

In addition to the spectrometer sensitivity to polarization, an unpredictable behavior of the optic fiber bundle output was found in the condition of the input polarized light. With un-polarized light, the fiber bending has very few effects. But with polarized light, the bending consequence is catastrophic. The multiple

internal reflections, inside the optical fiber, are suspected for the randomization of the input polarization angle. In this experiment, the same measurements as for the spectrometer sensitivity were repeated, but with different fiber bending.

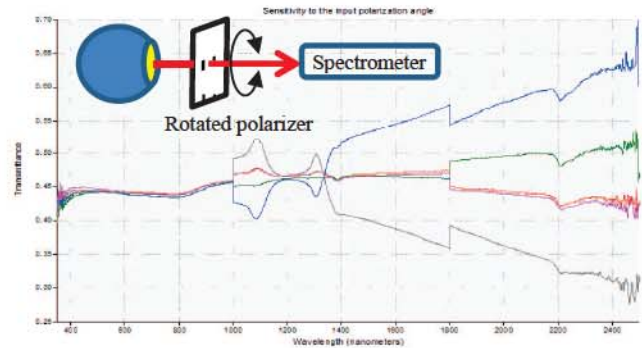


Figure 3. Variation of the spectral response with the rotation of the polarizer placed at the optical entrance.

As it shown in Fig.4, the spectral response changes considerably even for a small fiber bending, although the polarizer is not rotated (i.e. for the same input polarization). This was never observed in non-polarized light.

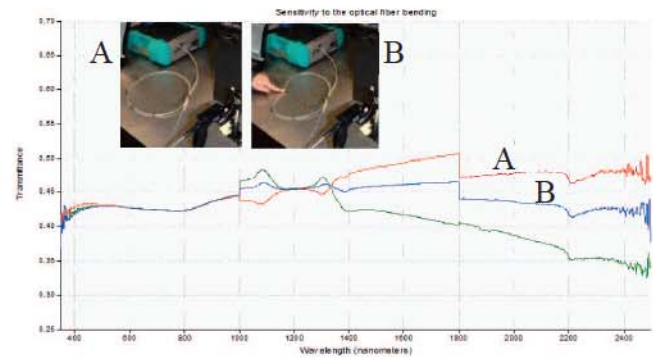


Figure 4. In presence of polarized light, variations of the spectrometer response for 3 cases of gentle optical fiber bending.

In order to see the reaction of the instrument to the polarization for each wavelength, spectra ' $S(\lambda, \theta)$ ' were acquired for all input polarization angles ' θ ', by rotating the input polarizer by step of 5 degrees for two different fiber bendings. From these measurements, the polarization axes ' θ_{max} ' providing the maximum sensitivity (also call the privileged polarization angle) were measured for all wavelengths.

The spectral sensitivity to the polarization was determined by calculating the degree of linear polarization (DOLP) of the spectrometer response. This is calculated with:

$$DOLP(\lambda) = \frac{\max_{\theta}(S(\lambda, \theta)) - \min_{\theta}(S(\lambda, \theta))}{\max_{\theta}(S(\lambda, \theta)) + \min_{\theta}(S(\lambda, \theta))} \quad \text{Eq. 1}$$

where ' $\max_{\theta}(S(\lambda, \theta))$ ' is the maximal spectral response, which occurs at the angle ' θ_{max} ' for the wavelength ' λ ', and ' $\min_{\theta}(S(\lambda, \theta))$ ' is the minimal spectral response, which occurs at ' (λ, θ_{min}) '.

The calculated DOLP for two different optical fiber bendings are shown in Fig. 5. This figure shows that some wavelengths are

not sensitive to the polarization (particularly in the visible and NIR band), while other wavelengths are extremely sensitive to the polarization. Basically, the DOLP increases with the wavelength.

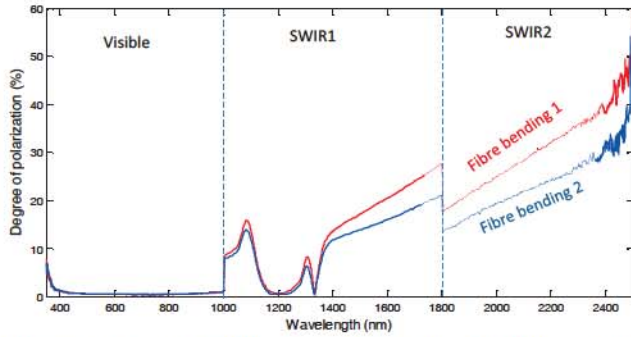


Figure 5. Spectral degree of polarization (DOPL) of the spectrometer for two different fiber bendings

But the fiber bending has also an effect on the DOLP. In general the pattern is similar but not the amplitude. This means that the optical fiber not only changes the output polarization angle, but with some bending configurations (which change the pattern of internal reflections) it may attenuate the sensitivity to the polarization.

During this experiment, the value of ' θ_{max} ' was measured and this experiment showed two facts: 1) changing the fiber constraint (bending) rotates considerably the output polarization axis by an unpredictable amount (shown in [4]) and 2) the output polarization angle is different for each band (the ASD spectrometer has 3 gratings and 3 detectors) but is practically constant within a spectral band. Visible and SWIR2 have a unique polarization angle (for a specific fiber bending). However, in the middle of the SWIR1 waveband near 1330 nm, where the inflection point was observed in Fig. 3, the polarization angle shifts suddenly by 90 degrees. Vanderbilt et al. [3] already indicated that the ASD spectrometer is responsible for measurement error at this wavelength. He mentioned that the optical fiber has an absorption line at this wavelength, but this does not explained the polarization angle shift, except, maybe, for a change in the fiber propagation mode. Another possible explanation for this phenomenon is the behavior of the oscillating grating [4].

3.3. Depolarizer – is it good problem solution?

The use of a depolarizer between polarizing components and spectrometer seems to make sense [5]. In fact, this makes things worst. We have tested a quartz-silica wedge depolarizer. This element creates a spatial pseudo-random polarization rotation. By integrating over the appropriate surface, a 0-360 degrees flat distribution of the polarization angles should make the light beam similar to an unpolarized light. But, such a flat distribution was never obtained. The effectiveness of the depolarizer was tested for two different apparent surfaces (' D_f ' for the full surface and ' D_p ' for only a smaller part of the surface). The raw spectra (for the setup: integrating sphere → polarizer → depolarizer → spectrometer) are shown in Fig. 6. In each setup, the signal is measured for the polarization angle at 0, 45, 90 and 135 degrees.

As result, the depolarizer succeeds '*partially*' to depolarize the signal. The signals for different polarization angle have all the same amplitude, whatever is the polarization angle. However, it creates ripple-like strong artefacts. There is always a polarization residue that depends on the wavelength.

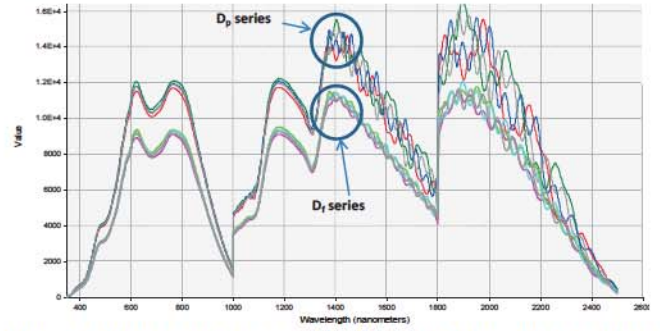


Figure 6. Raw spectra for acquired for the polarization angle 0, 45, 90 and 135 degrees and for the complete depolarizer surface (D_f) and then for only a partial surface (D_p).

This experiment illustrates that the polarized signal can be depolarized, but the polarization residue is out of control. In conclusion, the use of a depolarizer seemed to be a good idea, but in practice it is a source of trouble. Therefore, it was decided not using this element in the goniometer. The sensitivity of the spectrometer to the polarization angle has to be controlled by using an adequate measurement protocol.

4. ACQUISITION PROCEDURES

Considering the spectrometer sensitivity to the polarization, which generates measurement artefacts, two acquisition procedures was developed, which produces valid measurements and where the polarization artefacts are cancelled. These procedures take also in consideration the possible non-uniformity of the illumination and the spatial distribution of the sensor sensitivity in the FOV of the optical entrance.

Because of all possible unknown, a BRDF is always measured relatively to a known surface of reference; the Spectralon. Even if it is not perfect, the Spectralon is the best known close-to-Lambertian surface. By comparing sample and Spectralon measurements, the illumination and sensor (hard to model) functions are removed from the equations. When measuring the Spectralon ' $S(\lambda)$ ', a spectrum is acquired with all its setup-dependent spectral artefacts (aspect angles, polarization angle, sensor spectral response, light spectrum, etc.). Then the sample is measured exactly in the same conditions: ' $M(\lambda)$ '. At the end, when the sample spectrum is divided by the measured Spectralon spectrum, the spectral artefacts disappeared from the equation, leaving a correct sample measurement. It only remains to multiply this spectral ratio by the real Spectralon reflectance spectrum ' $\rho_{Spectralon}(\lambda)$ ' (from a calibration file) to produce the absolute material reflectance spectrum. Thus, the classical reflectance (ρ) measurement (Eq.2) is given by:

$$\rho_{sample}(\lambda) = \frac{M(\lambda)}{S(\lambda)} \rho_{spectralon}(\lambda). \quad \text{Eq. 2}$$

In the case of polarized conditions and with unpredictable optical fiber behavior become:

$$\rho_{sample}(\theta_i, \phi_i, \theta_r, \phi_r, \vartheta, \lambda) = \frac{M(\theta_i, \phi_i, \theta_{rn}, \phi_{rn}, \vartheta, \lambda)}{S(\theta_i, \phi_i, \theta_{rn}, \phi_{rn}, \vartheta, \lambda)} \rho_{spectralon}(\theta_i, \phi_i, \theta_r, \phi_r, \vartheta, \lambda) \quad \text{Eq. 3}$$

where $M(\theta_i, \phi_i, \theta_{rn}, \phi_{rn}, \vartheta, \lambda)$ and $S(\theta_i, \phi_i, \theta_{rn}, \phi_{rn}, \vartheta, \lambda)$ are the measurements of the material and Spectralon respectively for given polarization angle ϑ and light-sensor geometry defined by light

source nadir elevation and azimuth (θ_i, ϕ_i) and detector nadir elevation and azimuth (θ_r, ϕ_r) . The extra index 'n' is for the n^{th} optical fiber displacement (bending). This means that two measured signal, for the same geometric configuration, are not necessary equivalent if the detector is displaced and replaced. The optical fiber creates a random-like polarization rotation. To be able to compare 'M' and 'S', they must have the same 'n' index. Finally, to calculate the material BRDF ' ρ_{sample} ', it is also necessary to know into detail the spectro-polarimetric BRDF of the Spectralon, i.e.: ' $\rho_{\text{spectralon}}(\theta_i, \phi_i, \theta_r, \phi_r, \lambda)$ '.

The accurate method consists in measuring systematically the Spectralon and the sample. But this method implies that every time something is changed (polarization angle, light or sensor displacement) the goniometer is systematically recalibrated by re-measuring the Spectralon, which slow down considerable the acquisition sequence for a complete BRDF measurement.

A quicker procedure can be performed by measuring the BRDF in the BRDF reciprocal domain. Rather than moving the sensor, which displaces the optical fiber and requires recalibration every time, this is the light that is moved and the sensor remains steady. Furthermore, rather than moving both light and sensor in azimuth, only the light is moved by the equivalent angle ' $\phi_i - \phi_r$ '. Also, the sample holder is motorized, so the sample is rotated by the angle ' $-\phi_i$ ', preserving rigorously the scene geometry, which may be important for anisotropic material.

This 'acquisition domain' is almost equivalent to the classical BRDF domain where the light source is steady and the sensor is moving, scanning the hemisphere (excepted for the illumination change). It provides the real BRDF, for given incident light position. In fact, it measures: ' $\rho_{\text{sample}}(\theta_i, \phi_i - \phi_r, \theta_r, 0, \lambda)$ '. In this case, the Spectralon does not need to be re-measured every time the light is displaced. After having measured the Spectralon once, the sample can be measured several times for various light positions (θ_i, ϕ_i) . This speed up the measurement sequence considerably.

However, the intensity of the illumination on the target surface changes when the light elevation ' θ_i ' is changed and this requires to be corrected. For the classical case where the light beam is perfectly collimated, this is the well-known ' $1/\cos(\theta_i)$ ' illumination correction factor. Otherwise, for a conical light beam (and possibly with a non-uniform distribution) the ' $1/\cos(\theta_i)$ ' function must be replaced by a more realistic function. Also, the optical footprint changes with the sensor elevation ' θ_r ', which changes the perception of the illuminated target.

In the present context, the summary of all these sensor response alterations are represented by the function 'G', which is called the 'Goniometer BRDF-Error Function'. For a specific sensor and light positions, this function is the recording of the basic ' $\cos(\theta_i)$ ' illumination attenuation multiplied by the variable instrument response for various angle combination. Considering that the illumination might not be uniform and considering that the sensor sensitivity is not uniformly distributed inside footprint, the goniometer does systematic measurement errors. But in the same angular conditions, it does exactly the same error. Therefore, this systematic error (The Goniometer BRDF-Error Function) can be measured and modeled.

Basically, when measuring a known surface (a Spectralon of reference), this is the recording of *the difference between what the goniometer is measuring and what it should have measured*. The maximum of G occurs when the light is at zenith ($\theta_i=0, \phi_i=0$) and the sensor as close as possible (example: $\theta_r < 5^\circ, \phi_r=0$), i.e.

$G(0, 0, \theta_r, 0) = 1$. Thereafter, the 'Goniometer BRDF-Error Function' could be estimated for all acquisition geometry with:

$$G(\theta_i, \phi_i, \theta_r, \phi_r) = \frac{\rho_{\text{spectralon}}(0, 0, \theta_r, 0)}{\rho_{\text{spectralon}}(\theta_i, \phi_i, \theta_r, \phi_r)} \frac{S(\theta_i, \phi_i, \theta_r, \phi_r)}{S(0, 0, \theta_r, 0)} \quad \text{Eq. 4}$$

Knowing this instrument function $G(\theta_i, \phi_i, \theta_r, \phi_r)$, it is not necessary anymore to measure the Spectralon for each light source displacement. The material BRDF can be calibrated with Eq. 5, which is the result of the merging of Eqs. 3 and 4.

$$\rho_{\text{sample}}(\theta_i, \phi_i - \phi_r, \theta_r, 0, \lambda) = \frac{M(\theta_i, \phi_i - \phi_r, \theta_r, 0, \lambda)}{S(0, 0, \theta_r, 0, \lambda)} \frac{G(0, 0, \theta_r, 0)}{G(\theta_i, \phi_i - \phi_r, \theta_r, 0)} \rho_{\text{spectralon}}(0, 0, \theta_r, 0, \lambda) \quad \text{Eq. 5}$$

Note that the 'n' index ' θ_{rn} ' is still the measurement representation. This means that if the sensor is displaced, the Spectralon needs to be measured again, because of the randomization of the polarization angle caused by the optical fiber displacement. Otherwise, the goniometer can acquire a long measurement sequence for the material of interest without recalibrating the instrument each time. Even if the instrument is doing systematic measurement errors, the measured spectrum is corrected later by applying the 'Goniometer BRDF-Error Function'.

5. CONCLUSION

Despite of the goniometer defaults (sensitivity of the spectrometer to the polarization, random polarization rotation caused by the displacement of the optical fiber, non-uniform light distribution and sensitivity variation in the FOV), it is still possible acquiring very good spectro-polarimetric measurements with this instrument. But a strict calibration and operation procedure must be used. Two operation procedures are explained in this paper; the accurate one and the quick one which allows us to maintain the spectral response under control.

6. REFERENCES

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